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by

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ABSTRACT

The residence time of water and suspended particles in Fort Point Channel, a sub-region of Boston Harbor containing a major combined sewer overflow and highly contaminated sediment, was determined during three field surveys by measuring the disappearance of fluorescent tracers from the water column. Flushing by advective movement was quantified using Rhodamine WT dye, a dissolved tracer which has negligible interaction with suspended sediment. The fate of suspended particles was inferred from measured concentrations of fluorescent pigment particles which were initially well mixed with Rhodamine dye and which have a size range and settling velocity comparable to the sewage particles of interest. Dye and particle concentrations were measured by fluorescent spectroscopy of water samples obtained throughout the channel over a week following tracer introduction. Dye measurements indicate that channel water is replaced on a scale of 1 to 2.7 days, depending on tidal amplitude and phase during tracer release, and the magnitude of freshwater inflow. Ratios of normalized particle concentration to dye concentration effective deposition velocities of 1.5 to 3.3 m/d; this is an order of magnitude faster than observed in laboratory settling columns suggesting that removal of suspended tracer particles from Fort Point Channel during our surveys may have been the result of scavenging by a bottom "fluff" layer. This finding is consistent with our previous observation of particle deposition in Salem Sound, Massachusetts, and in controlled laboratory studies of particle aggregation at the sediment-water interface.

INTRODUCTION

Urban harbors can receive raw and partially treated sewage from a number of sources. For example, Figure 1 shows the location of combined sewer overflows (CSOs) in the Boston Harbor area, some of which currently discharge as often as about once a week (MWRA, 1994). In addition to being an aesthetic nuisance, these particle-laden flows contain pathogens, toxic chemicals, and biochemical oxygen demand which can affect human and aquatic health.

In order to better understand water column dispersion and initial deposition of sewage-derived particles, three fluorescent tracer experiments were performed in Fort Point Channel, a portion of Boston Inner Harbor with approximate average dimensions of 1650 m long, 140 m wide and 6 m deep (MWL; Figs. 1 and 2). Nominal dates of the three experiments were November 1989, May 1990, and July 1991. Fort Point Channel was chosen, in part, because the CSO at the channel head (designated BOS070) is one of the largest discharging directly into Boston Harbor. Fort Point Channel is also part of the inner harbor (hence several kilometers from beaches and shellfishing areas in the outer harbor), and it is critical to CSO planning to understand how dissolved and particle-bound pollutants discharged in the inner harbor are transported to the outer harbor. Finally the channel geometry and multiple bridge crossings allow for easy sampling. On the other hand, BOS070 is perhaps the most complicated CSO because it receives combined sewer overflow from a number of different regulators as well as some storm water runoff. As such, direct monitoring of the aggregate overflow rate is very difficult and was not attempted.

DATA COLLECTION

During each of the three experiments, fluorescent tracer(s) were discharged continuously at the head of Fort Point Channel (mouth BOS070 culvert) over a period of about two hours and monitored throughout the channel for about one week.

The tracers included red Rhodamine WT dye and Saturn Yellow Day-Glo fluorescent paint. Rhodamine WT, which fluoresces orange, comes as a 20% solution (specific gravity of solution = 1.13 for the batches used) and is available from Crompton and Knowles Corp., Charlotte, NC.

The fluorescent paint, which fluoresces over a broad range of yellow and green, is a 50% solution of suspended AX-17 pigment particles (specific gravity of solution = 1.19) manufactured by Day-Glo Color Corporation of Cleveland, Ohio. The particles are amorphous, non-porous organic resin particles, with diameters ranging between about 0.1 and 20 microns. Choice of this tracer was guided by previous experience using a similar paint of different color (Rocket Red, also manufactured by Day-Glo Color Corporation) in a field study of particle deposition in nearby Salem Sound (Newman *et al.*, 1990b). Additional information concerning settling and aggregation characteristics of the paint are documented in Newman *et al.* (1990a).

During the first experiment, only Rhodamine WT was used, and the dye was dispensed *quasi*-continuously by pouring equal quantities into the culvert mouth every ten minutes. During the second and third experiments, a solution of dye and paint was used. To encourage dispersal in these latter studies, the tracers were thoroughly stirred in a pair of 1000 liter tanks with a mixture of one part tracer solution to ten parts ambient channel water. The mixture was then dispensed continuously to the channel by gravity through a hose. Quantities of dye and paint used in each experiment are listed in Table 1.

Monitoring was conducted by collecting discrete samples from bridges and the channel banks during intervals of about one to two hours surrounding low slack tide. During the first two to three days of each experiment, surveys were conducted at each low tide, while during the latter phases, surveys were conducted at greater intervals. In the following, sampling times are defined in terms of the number of tidal cycles after discharge, *e.g.* 1T, 2T, etc. Figure 2 shows typical horizontal positions used for tracer sampling. Generally surface samples were collected at each station while vertical samples (1.5 m, 3m, and 5 or 6 m) were also collected at the central stations.

Tracer samples were collected in amber bottles and brought to the laboratory for analysis. During the first experiment, concentrations were measured using a Turner Designs Model 10 filter fluorometer with light source and emission and excitation filters supplied by Turner Designs for use with Rhodamine WT. During the second two experiments (with both dye and paint), a surfactant was added. The samples were then sonicated briefly to liberate tracer from the walls,

and analyzed for tracer particles and Rhodamine WT using a fluorescence spectrometer (Perkin-Elmer). Excitation and emission wavelengths of 420 nm and 506 nm for the paint and 555 nm and 575 nm for Rhodamine WT were found to yield peak sensitivity and negligible interference between the two tracers. Sample concentrations for both tracers in all surveys were established by reference to laboratory standards corrected for measured background concentration. Our convention has been to define concentration and mass of dye based on the original 20% solution while the concentration and mass of paint is relative to pure AX-17 particles.

Several other tracers were monitored by research colleagues including temperature and salinity, fecal coliform and *Enterococcus*, suspended solids, and the concentrations of various trace metals. In addition, during the third study, surface and near-bottom Rhodamine WT measurements were taken near the channel mouth to better understand what fraction of tracer transported from the channel to the Inner Harbor on ebb tide returns with the following flood tide. Fluorescence was monitored by a Turner Designs Model 10 Fluorometer set up in continuous sampling mode. Details concerning these studies as well as further information concerning the tracer experiments are contained in Adams and Stolzenbach (1992) and Stolzenbach and Adams (1997).

DATA ANALYSIS

Two quantities often derived from tracer studies are the hydrodynamic residence time τ and the flushing rate k_f. If the tracer were discharged continuously, and reached *quasi*-steady-state conditions (repeating each tidal cycle), τ could be defined by the total mass of tracer in the channel divided by the rate of tracer delivery, $\dot{m}$, or

$$\tau = \frac{\int c dV}{\dot{m}} \qquad (1)$$

where c is tracer concentration and V is the channel volume. The flushing rate, k_f, would simply be τ^{-1}. Note that both k_f and τ are functions of tracer discharge location.

For an instantaneous release, τ is defined by the first moment of the residence time distribution f(t) or

$$\tau = \frac{\int_0^\infty f(t)tdt}{\int_0^\infty f(t)dt} \tag{2}$$

If the amount of tracer remaining in the channel is M(t), and the initial amount is M(0), then the total amount that has left, up to time t, is

$$\int_0^t f(t)dt = M(0) - M(t)$$

or

$$f(t) = -\frac{dM(t)}{dt} \tag{3}$$

Substituting Eq. (3) into Eq. (2) and simplifying yields

$$\tau = \frac{1}{M(0)}\int_0^\infty M(t)dt \tag{4}$$

That is, τ is the zeroeth moment of the time-varying distribution of total mass in the channel, divided by initial mass. For an instantaneous release, τ will be a function of the time (phase of the tide) as well as location of the tracer release.

Comparison over time of the concentration of paint and dye (or their spatial integration-mass) allows one to quantify the rate of paint deposition. Defining the mass of paint and dye suspended (dissolved) within the channel water as M_p and M_d, respectively, we can write

$$\frac{d}{dt}M_p = -k_s M_p - k_f M_p \tag{5}$$

$$\frac{d}{dt}M_d = -k_f M_d \tag{6}$$

where k_s is the net deposition (or settling) rate of paint and k_f is the previously defined flushing rate. If we assume that k_f is the same for paint and dye, then one can combine Eqs. (5) and (6) to derive

$$\frac{d}{dt}\left(M_p / M_d\right) = -k_s\left(M_p / M_d\right) \qquad (7)$$

Thus k_s can be determined either from the difference in the rates of decrease of M_p and M_d (Eqs. 5 and 6) or the rate of decrease in their ratio (Eq. 7).

EXPERIMENTAL CONDITIONS

Table 1 summarizes ambient conditions during the three experiments. The tidal range at the time of discharge (defined here as the height of the nearest high water minus the height of the following low water) varied from 2.6 to 4.1 m, which compares with an average tidal range (mean high water minus mean low water) in Boston Harbor of 2.9 m (NOS, 1991). The comparatively high value of 4.1 m for the last experiment would suggest relatively fast flushing. While the three tracer injections were all made in the morning, the phase of the tide also varied for the three experiments. Because the last two experiments discharged during high slack and ebb respectively, these would be expected to flush the most rapidly.

Figure 3 plots hourly rainfall measured at Logan Airport during the time of each experiment, and Table 1 indicates that total rainfall during the previous 30 hours leading through the tracer release varied from 0.11 to 0.72 inches (2.8 to 18 mm). As indicated previously, direct measurements of freshwater inflow were not made, but salinity measurements at the culvert indicate that freshwater was discharged during all three experiments. The first experiments occurred during a period of dry weather, but culvert salinity measurements suggested a steady freshwater inflow, which was later attributed to a leaky regulator. By estimating the volume of freshwater in the channel and using the residence time of 2.7 days computed from dye measurements (see below), a dry weather overflow rate of about 1 MGD (0.04 m^3/s) was estimated during this experiment. The second tracer release occurred at the end of a steady rainfall which totaled 0.72 inches. Culvert salinity measurements indicated that freshwater was released intermittently over several tidal cycles following the rainfall and a computer model of the combined sewer system calculated a total freshwater discharge of $1.3 \times 10^4 m^3$ (Heineman, 1990) or about

1% of the channel volume at MWL. The computed CSO hydrograph is plotted as dotted lines in the middle panel of Figure 3. The intermittency of the observed freshwater release was attributed to the fact that the peak overflow occurred near high tide, which caused it to back up and be released over several subsequent tidal cycles. The third tracer release occurred several hours after a rainfall of 0.52 inches (13 mm). Culvert salinity measurements suggested a discrete CSO event lasting for less than one tidal cycle. CSO model predictions were not available for this experiment.

Temperature and salinity measurements taken before each survey showed that the channel was well-mixed with respect to temperature and showed only modest salinity differences (less than 2 PSU) between surface and bottom, except during the first experiment which experienced a dry weather overflow. Sometimes (both prior to and during the experiments) the lowest salinity in the channel was observed at the channel mouth which was attributed to the influence of the Charles River which discharges to the inner harbor about 3 km north of Fort Point Channel (Fig. 1). On an annual basis the freshwater released from the Charles River is several hundred times that discharged from CSOs in Fort Point Channel (Alber and Chan, 1994; MWRA, 1994), making it difficult to use freshwater as a tracer.

RESULTS OF DYE MEASUREMENTS

As an example of the dye measurements, Figure 4 shows a longitudinal-vertical section of dye concentration taken during the second low tide survey, approximately 22 hours after dye release during the first experiment. The data indicate a pattern of circulation in Fort Point Channel in which water from upstream is dispersed longitudinally in the downstream direction and vertically into the deeper parts of the channel. The dye concentration becomes relatively homogeneous throughout the channel in about two days. The time variation of surface concentration at sampling stations during the first experiment is shown in Figure 5.

Figure 6 shows the distribution of total dye mass in the channel for the first experiment based on spatial integration of dye concentration measurements collected at low tide. Error bars in Figure 6 indicate estimated uncertainty ($\pm 1kg$) associated with variability in background

concentration. The value of τ for this distribution, based on Eq. (4), is about 2.7 days making the flushing rate $k_f \equiv \tau^{-1} \cong 0.36d^{-1}$. Note that the flushing rate has more meaning for a continuous discharge in which case, following Eq. (1), k_f defines the rate of mass removal that just balances the rate of injection. For an instantaneous discharge, the rate of removal is not constant as indicated in Figure 6. Because the discharge is to the head of the channel, the initial rate of removal (indicated by the absolute value of the slope of the graph) is slower than the subsequent rate. The difference is probably accentuated in this study because the dye was released during flood tide resulting in initial transport upstream into the culvert. For reference, a constant rate of $k_f = 0.36d^{-1}$ is indicated by the straight line in Figure 6.

Dye mass versus time for the other two experiments is plotted in Figures 7a and 8a, and Table 2 summarizes residence times for the three experiments computed from Eq. (4). During the first two experiments the time was about 2.5 days while during the last experiment it was about 1.0 days. Due to variability in background concentration, errors in spatial integration, and other factors, we estimated the uncertainty in each value to be approximately $\pm 25\%$. The large difference between the first two experiments and the last experiment may be due to a combination of factors including the tidal range, the phase of the tide during tracer release, and freshwater inflow.

Tidal Mixing

The first factor can be assessed using simple tidal mixing concepts. The simplest model assumes tidal prism mixing whereby incoming water during flood tide is mixed completely with channel water and a fraction equal to the tidal prism divided by the high tide channel volume is flushed during ebb tide. The theoretical tidal prism flushing time assumes that none of the mixed water that exists during ebb returns during the following flood, so the theoretical time would be

$$\tau_{tide} = \frac{(H + a_o)T}{2a_o} \qquad (8)$$

where a_0 is the tidal amplitude, H is the average channel depth at MWL, and T is the tidal period. Using $H = 6m$, $2a_o = 2.9m$ and T = 12.4 hr yields a theoretical time of approximately 1.3 days. The tidal prism method provides a lower bound for the flushing time (due to purely tidal processes) because it assume complete mixing within the channel and assumes no return on flood. Also note that the time is approximately (inversely) proportional to the tidal amplitude a_0. Other tidal mixing theories, such as Ketchum's (1951) modified tidal prism approach, assume uniform mixing only over a segment of the channel that is proportional to the local tidal excursion. Such theories give longer residence times and predict that residence time is proportional to the square of the tidal amplitude. A similar quadratic dependence is obtained if one estimates a tidal dispersion coefficient, from dimensional considerations, as being proportional to a local tidal excursion squared divided by tidal period (Officer, 1976).

In view of the above, Table 2 includes two sets of rescaled residence times. The first (line 4) is obtained by multiplying the observed times by the ratio of the actual tidal range during the experiment to the average tidal range in Boston Harbor. The second (line 5) multiplies the observed times by the ratio squared. Note that the rescaled values show much less variation among experiments, reflecting the strong influence of the extreme tidal range during the third experiment. Rescaling the residence time still yields the longest time for the first experiment, which can be attributed to the fact that the tracer was released during flood tide and hence was initially (partially) trapped within the BOS070 culvert. Rescaling also still yields the shortest time for the third experiment. This may be due to the fact that this experiment experienced a concentrated CSO flow at BOS070. Hence we could expect that density currents played a greater role in transport during this experiment.

Density Currents

The relatively small freshwater inflow, as well as its intermittency, precludes the establishment of a classical estuarine circulation in Fort Point Channel. However, it is possible to show that density currents can play a significant role in channel flushing. By assuming a balance between hydrostatic pressure due to buoyancy and interfacial friction in a prismatic tideless channel

of length L and width W, Adams and Stolzenbach (1992) derive an expression for the residence time τ_{den} of a volume v_0 of freshwater discharged instantaneously to the head of the channel:

$$\tau_{den} = \frac{1.2 L^{5/2} f_i^{1/2} W}{\left[\frac{\Delta\rho_0 g S}{\rho}\right]^{1/2} v_0} \tag{9}$$

where $\Delta\rho_0 / \rho$ is the normalized density difference between saltwater and freshwater, g is the acceleration of gravity, S is the initial dilution experienced at the head of the channel and f_i is an interfacial friction factor. τ_{den} is defined as the time required for 63% of the freshwater to exit the channel. Taking W = 140 m, L = 1650 m, $\Delta\rho_0 / \rho = 0.023$ (corresponding to an ambient salinity of 30 psu), g = 9.8 m/s^2, v_0 = 1.3 x 10^4 m^3 (the predicted freshwater inflow volume during the second experiment) , S = 5 (corresponding to an average surface to bottom salinity difference after mixing of 6 psu), and f_i = 0.02 (Harleman and Stolzenbach, 1972), yields $\tau_{den} \cong 2.2$ days, or somewhat longer than the tidal prism flushing time.

RESULTS OF PAINT MEASUREMENTS

Measured paint concentrations were also spatially integrated. Figures 7b and 8b depict the decline of the normalized ratio R of paint to dye mass for the second two experiments, where

$$R = \frac{M_p(t)/M_p(0)}{M_d(t)/M_d(0)} \tag{10}$$

The data are plotted with error bars indicating estimated uncertainty ($\pm 10kg$) caused by variation of background paint concentration.

The net deposition rate was computed from Eq. (7) using least squares, yielding k_s = 0.25 d^{-1} and 0.55 d^{-1} for the second and third experiment, respectively. These values overlap the lower limits of the hydrodynamic flushing rate (k_f = 0.4 to 1 d^{-1}) suggesting that up to about half of the paint is depositing within the channel, while the rest is being flushed to the inner harbor. Using a water depth of 6 m, net deposition rates of 0.25 to 0.55 d^{-1} correspond to settling velocities of 1.5

to 3.3 md^{-1} which are somewhat higher than the range of values found in earlier studies with similar tracers conducted in Salem Sound (Newman *et al.*, 1990b). As indicated below, they are also substantially above the general range expected for discrete settling.

Laboratory Settling Column Tests

It is of interest to compare the net deposition rates observed in the field of 0.25 to 0.55 d^{-1} with rates expected from discrete gravitational settling (Stokes settling). To the extent that the former are significantly larger, the difference could indicate the presence in the field of other settling processes such as particle aggregation.

To explore this issue, several laboratory settling experiments were undertaken. Observations were made of the decrease in relative fluorescence over time in five columns containing water that varied in both origin and tracer concentration. In Columns A, B, C and E ambient water from Fort Point Channel was mixed with tracer, yielding initial tracer concentrations of 10^{-7}, 10^{-5}, 10^{-3} and 10^{-1} g/g, respectively. In Column D the tracer concentration was 10^{-3} g/g, but distilled water, rather than channel water, was used as the solvent. The water columns were 75 cm high, and began with well-mixed conditions (*i.e.* homogeneous tracer concentration throughout each column). The water columns were sampled at 1, 5, 24, 50, and 96 hours after settling had started, through ports located near the bottom, the middle, and the top of the water columns. Samples were analyzed with our spectrofluorometer and a column average fluorescence intensity was defined by weighting the top and bottom measurements by 25% and the middle measurement by 50%.

Except for Column A, all water columns showed monotonic decreases in fluorescence intensity. Column A showed an initial increase in fluorescence which we think might be due to the difficulties involved in measuring fluorescence at the relatively low concentration (10^{-7} g/g). For the remaining columns the rate of fluorescence decrease was somewhat faster than obtained by Newman *et al.* (1990a), based on experiments with a similar fluorescent paint (Rocket Red), but considerably slower than the range obtained in the field. The difference between laboratory and field rates seems to confirm a difference between the settling process in the field and the one in the

laboratory. It is also noteworthy that no significant difference was observed between Columns C and D which contained similar initial concentrations but different solvents. The fact that Column C with Fort Point Channel water did not settle faster seems to rule out the role of aggregation between paint particles and ambient particles in explaining the enhanced settling in the field. This leaves aggregation between paint particles and bottom (fluff layer) sediment as a likely cause of the enhanced settling in the field. This is the hypothesis set forth by Newman *et al.* (1990b) and Stolzenbach *et al.* (1992).

To compare the laboratory results with Stokes law, it is necessary to relate fluorescence intensity to tracer concentration. For dissolved fluorescent tracers, the relationship is nearly linear and is determined using calibration curves generated from laboratory standards. However, the fluorescence of paint particles is proportional to the particle diameter squared while concentration is proportional to particle diameter cubed. For a given initial particle size distribution, discrete settling results in an initial loss of the largest particles resulting in a more rapid decline in concentration than fluorescence. To account for this affect, a model was developed based on the initial particle size distribution measured by Newman *et al.* (1990a). Discrete settling was assumed for each size fraction at a rate proportional to the diameter squared. The coefficient of proportionality was left unknown, but assumed to be the same for each size fraction. At a given time, the particle size distribution was obtained from the observed relative fluorescence and used to compute the relative tracer concentration. Average fluorescence intensities were used, obtained by averaging the fluorescence of each column, excluding Column A, at each time. The result was an averaged concentration at four times (5, 24, 49, and 96 hours).

Average concentration, normalized by initial concentration, is shown in Figure 9. From this figure a time-averaged net deposition rate k was computed and compared to the one predicted by Stokes law based on the assumed particle size distribution. The experimental model coefficient was greater by a factor of 1.5 (*i.e.* settling in each size fraction was about 50% greater than predicted by Stokes). The discrepancy is not as large as it seems: it can in fact be caused by a

difference of only 22% between assumed and actual particle diameter in each size fraction. Such a possibility in not unlikely, given the wide range in particle diameters.

In addition to normalized concentrations from the laboratory, Figure 9 also displays normalized paint mass settling based on k_s from the field experiments. The mass of paint used here and in previous analysis has been calculated directly from fluorescence in anticipation that particle aggregation governs settling. If particle aggregation plays a role, then settling may be independent of particle size, in which case concentration is directly proportional to fluorescence. This was the tentative conclusion of Newman *et al.* (1990b) regarding their experiment in Salem Sound and, based on Figure 9, appears likely in our case as well. However, we emphasize the sample variability and uncertainty due to background concentration which underlie the dye and paint mass measurements which form the basis of the inferred settling rates in the field.

FURTHER DISCUSSION

Figure 10 plots the dye residence time distributions for the three experiments using Eq. (3) based on time-varying mass data in Figures 6-8. Data have been smoothed to reduce the noise in this figure. Since the area under each curve is unity, the mean residence time for each experiment is the first moment of the corresponding curve. We can note that, if the channel were spatially well-mixed, the residence time distribution would be $f(t) = e^{-t/\tau}$, while if there were plug flow, $f(t) = \delta(t - \tau)$; *i.e.* a spike at $t = \tau$. In general the shapes of the residence time curves suggest mixing patterns between well-mixed and plug flow. Again we note that the curve for the first experiment peaks last, reflecting the discharge during flood tide, while the curve for the last experiment peaks first and declines most rapidly, reflecting the rapid flushing.

Superimposed on the residence time curves are four first order "decay curves" of $\exp(-kt)$ for k = 0.25, 0.5, 1.0 and 2.0 day^{-1}. The ratio of the time-integrated flux of a non-conservative contaminant exiting the channel, in comparison to the quantity discharged, can be estimated as

$$F = \int_0^\infty e^{-kt} f(t) dt \qquad (11)$$

As an example, consider the second experiment with intermediate flushing characteristics. For $k = 0.25 d^{-1}$, we compute $F \cong 0.55$; identifying $k = k_s = 0.25 d^{-1}$ as a representative net deposition rate of paint suggests that 45% of the paint settles in the channel. Similarly, measurements of fecal coliform conducted during this study and other studies suggest a disappearance rate of about $2 d^{-1}$. For k = 2.0 day^{-1}, $F \cong 0.15$ suggesting that 85% of the fecal coliform which are discharged disappear before they exit the channel.

The measured channel residence times of about 1 to 2.5 days can be compared with residence times for the larger waterbodies into which Fort Point Channel discharges. For example, Bumpus (1953) used Eq. (1) with salinity measurements to estimate the residence time of freshwater in the inner harbor of 2 to 10 days, depending on freshwater flow rate. These estimates have been supported by dye measurements analyzed using Eq. (4) by Hilton *et al.* (1997). Meanwhile, Stolzenbach and Adams (1997) summarize outer harbor residence times ranging from 3 to 10 days, reported by a number of investigators based on use of Eq. (4) applied to tracers discharged through the Deer and Nut Island wastewater outfalls (Fig. 1); a similar range has been found through numerical model simulation (Signell and Butman, 1992). Since each study pertains to water of different origin, the residence times can not be strictly added. However, their sum gives an approximate indication of the residence time of Fort Point Channel water as it is transported through the inner and outer harbors into Mass Bay.

SUMMARY AND CONCLUSIONS

Based on our three tracer experiments, we can draw the following conclusions. Residence times, based on tracer discharged at the channel head, were about 2.5 days for the first two experiments and 1 day for the third. Theoretical calculations suggest that flushing is controlled by both tidal mixing and density currents. The shorter time for the third experiment can be attributed

to the abnormally high tidal range, the timing of the tracer release (ebb tide), and the concentrated freshwater inflow.

Effective particle deposition velocities of 1.5 to 3.3 m/s were inferred from the latter two experiments based on the relative removal rates of dye and paint. These velocities are greater than expected from discrete settling or from laboratory settling column experiments. Together, this evidence suggests that the particle deposition in the field could be caused by aggregation of paint particles with bottom sediments in the channel, a mechanism suggested by Newman *et al.* (1990b) and Stolzenbach *et al.* (1992). This mechanism would be enhanced in the shallower upstream portion of Fort Point Channel by the rapid vertical transport due to tidal oscillations, which allows the more highly concentrated surface water to periodically contact the bottom sediment. This hypothesis is supported by the fact that the net deposition rate (as well as the flushing rate) was greater during the third experiment which had the larger tidal range.

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Table 1: Fort Point Channel Surveys

Date of tracer release	November 29, 1989	May 5, 1990	July 14, 1991
Time of release	0720-0850	0800-1000	0340-0555
Tidal phase during release (time of nearest high tide)	flood (1128)	high slack (0905)	ebb (0124)
Tidal range (m)	3.0	2.6	4.1
Rainfall at Logan Airport (within 24 hours)	0.11"	0.72"	0.52"
Observed freshwater flow	steady dry weather overflow	intermittent CSO discharge	concentrated CSO discharge
Number of surveys/duration	11 over 6 days	9 over 10 days	9 over 6 days
Dye released (kg of 20% solution)	11	22	22
Paint release (kg pure particles)	—	130	65

Table 2: Summary of Residence Times

	November, 1989	May, 1990	July 1991
Time τ (days)	2.7	2.6	1.0
Tidal range $2a_0(m)$	3.0	2.6	4.1
Tidal phase during tracer release	flood	high slack	ebb
Rescaled time $\tau\left(a_0/\bar{a}_0\right)$ (days)	2.8	2.3	1.4
Rescaled time $\tau\left(a_0/\bar{a}_0\right)^2$ (days)	2.9	2.1	2.0

FIGURE CAPTIONS

Fig. 1. Map of Boston Harbor including location of Fort Point Channel (modified from Leo, *et al.*, 1993)

Fig. 2. Plan view of Fort Point Channel showing typical sampling locations. Tracers were discharged to head of the channel at BOS070 culvert.

Fig. 3 Rainfall *vs.* time for three experiments: a) November 1989, b) May 1990, and c) July 1991. Dotted line in middle experiment is predicted CSO flow.

Fig. 4 Typical longitudinal-vertical section of dye concentration (mg/L) measured one day after tracer release during the November study.

Fig. 5 Surface dye concentration in Fort Point Channel, November 1989 experiment.

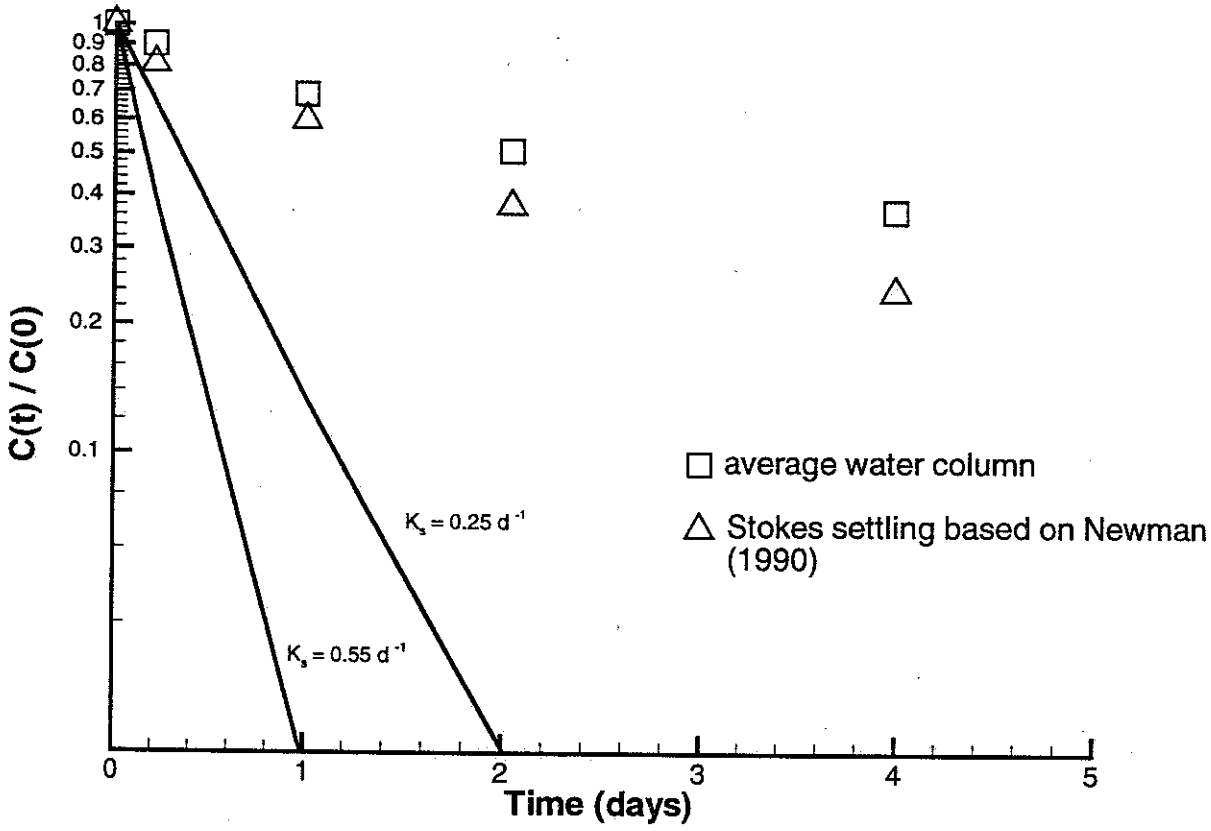
Fig. 6 Dye mass *vs.* time, November 1989 experiment.

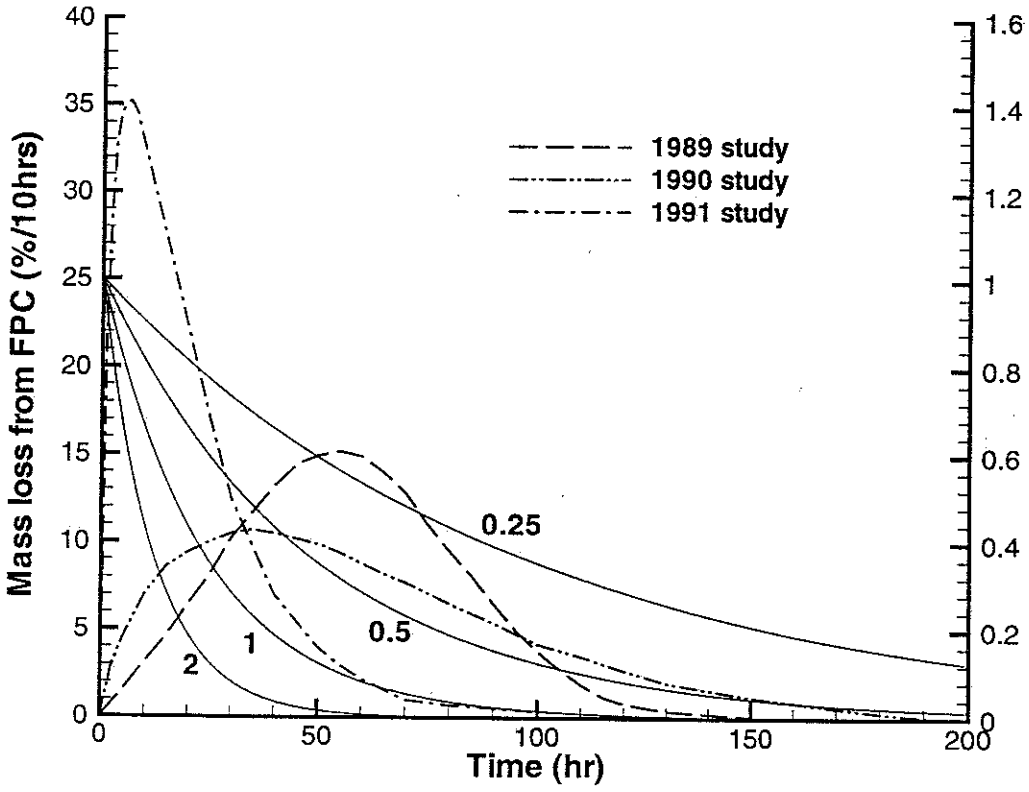
Fig. 7 Dye and paint mass *vs.* time, May 1990 experiment. a) dye mass, b) normalized ratio of paint to dye mass.

Fig. 8 Dye and paint mass *vs.* time, July 1991 experiment. a) dye mass, b) normalized ratio of paint to dye mass.

Fig. 9 Suspended paint concentration *vs.* time for laboratory settling tests.

Fig. 10. Residence time distributions in Fort Point Channel (left ordinate). First order (exponential) decay curves for rates of 0.25, 0.5, 1.0 and 2.0 d^{-1} (right ordinate).


C(t) / C(0)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
Time (days)
K_s = 0.25 d^{-1}
K_s = 0.55 d^{-1}
average water column
Stokes settling based on Newman (1990)


Mass loss from FPC (%/10hrs)
Time (hr)
1989 study
1990 study
1991 study
0.25
0.5
1
2
0
5
10
15
20
25
30
35
40
0
50
100
150
200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6